EASR

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

Sustainable management of plastic waste: Assessment of recycled biodegradable plastic market and projection for the future

Oludaisi Adekomaya* and Thokozani Majozi

NRF/DST Chair: Sustainable Process Engineering, School of Chemical and Metallurgical Engineering, Faculty of Engineering and Built Environment, University of the Witwatersrand, Braamfontein, Johannesburg 2000, South Africa

Received 16 September 2019
Revised 1 January 2020
Accepted 6 January 2020

Abstract

Global production of plastics has increased astronomically in the last five decades. This may not be unconnected with the rate of consumption of plastics owing to their increasing applications and good characteristics such as light weight, strength, durability, affordability, corrosion resistance and low production costs. Production of plastic materials accounts for 3 to 5% greenhouse gas (GHG) emissions globally. Reports from published works show that, as of 2015 alone, close to 6300 metric tonnes of synthetic plastic waste were generated, of which only 9% were recycled with 12% being incinerated, and a large proportion, 79%, discarded in the natural environment. Further studies show that a sizeable proportion, 12,000 metric tonnes, of plastic waste may annually find their way into the environment by 2050. The adoption of biodegradable materials to replace the conventional plastics has been proposed and implemented with varying environmental implications. In this paper, a sustainable approach to plastic wastes was examined, taking into consideration the emerging and developing world's attitudes about plastic waste management. Also discussed in this paper is the projection of the plastic waste market with particular reference to United States and China as global players in the industry. The concluding part of this paper focuses on future trends in plastic innovation with the evolution of nanoscale materials, bio-refining and most importantly cradle-to-cradle packaging materials. It is expected that this paper will assist various bodies involved in plastic waste management for developing better and sustainable methods.

Keywords: Plastics waste, Biodegradable market, Environment, Sustainability, New plastic material

Nomenclature

PBS Polybutyrate succinate
PBSL Polybutyrate succinate-co-lactade
PBSA Polybutyrate succinate-co-adipate
PCL Polycaprolactone
PE Polyethylene
PET Polyethylene terepythalate
PVC Polyvinyl chloride
PBST Polybutyrate succinate-co-adipate terephthalate
PCBS Poly(I-cystine-bisamide-g-sulfadiazine)
TPS Thermoplastic starch
PLA Polylactide, polylactic acid
PHA Polyhydroxyalkanoates
PP Polypropylene
PBT Polybutylate terepythalate
PUR Polyurethane

1. Introduction

Plastic waste management remains a challenge in many countries of the world. What is more worrisome is the level of generation and the growing difficulties among developing countries to control waste proliferation. The impact of plastic debris on our environment seems to have defied solution amidst climatic threats. In the past, plastic waste has been recycled and processed for other applications. Biodegradable materials have evolved. In the recent times, there seems to be more attention on future plastic materials than before in view of multiple environmental crises facing the world [1]. The concept of green materials has been proposed in many past works as a sustainable approach to waste management, but the modalities of implementation in many developing countries remain a mirage [2]. The societal concept of bio-based and biodegradable materials have impacted waste volumes, no doubt, but the end-of-life phase of some of the plastic materials has not been properly defined. In another work [3], it was clearly demonstrated that the innovations brought into the industry with the introduction of biodegradable polymers have significantly reduced waste volumes in some developed countries. However, this may not be realized in developing countries struggling with

*Corresponding author.
Email address: oludaisiyetunde@gmail.com, oludaisi.adekomaya@wits.ac.za
doi: 10.14456/easr.2020.24

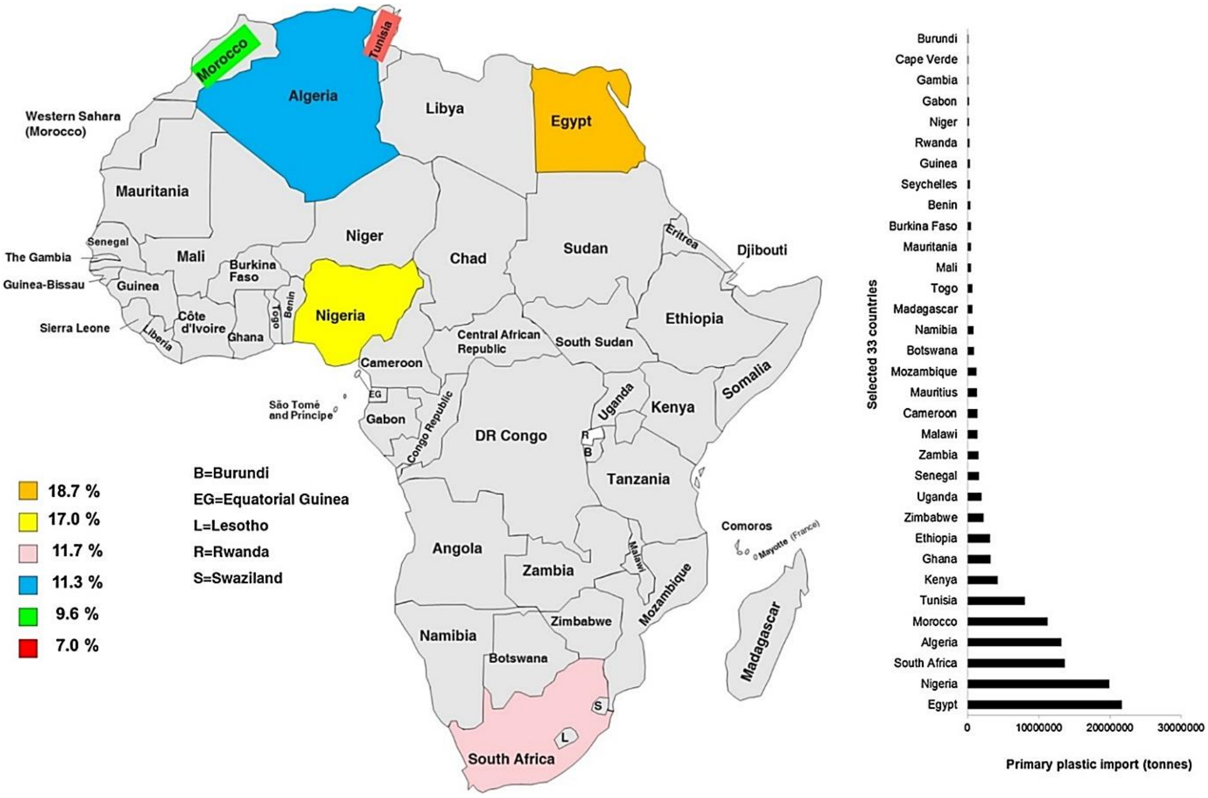

Figure 1 The six African countries with the highest import and use of plastic [4]

waste mitigation and control. In several emerging countries, some innovations have been realized in packaging, disposable materials and catering supplies. In other countries, some classes of bio-based polymers have been employed in wide range of applications owing to their biodegradability. Plastic consumption in six (6) developing countries is presented in Figure 1, indicating the various proportions of plastics imported by some of these countries. Part of the concern raised with these plastic imports is that only South Africa can effectively recycle its end-product waste, while the other African countries only add to their existing waste volumes in their respective countries.

At one time, China was the largest importing nation of plastics, as illustrated in Figure 2. The global market for plastic waste increased on several fronts, especially between 2006 and 2012. The competitive market for plastic waste is not as active now as China has exited the global market, fueling instability in the plastics market in several countries. The global demand for plastic waste from Southeast Asia has declined in view of new Chinese policies on waste management. In past times (between 2006 and 2012), imports from Asia were in high demand, ranging from 4.9 - 7.9 million Mt, depending on the industrial applications. Part of the economic friction between the United States and China may have contributed to sudden ban on plastic waste as the United States was a leading supplier of plastic waste to China. Figure 2 shows the projected plastic waste prior to the Chinese decision to end plastic waste imports. It can be seen that there was a consistent demand for waste plastic between 1990 and 2015 before the slow-down in China. During the period under review, Hong Kong remained the territory in which waste treatment was done as China controlled the supply chain in other regions in Asia. Several published papers [5-7] reviewed the International Recycling Markets for plastic wastes. Five cogent needs have been advanced:

i. Availability of national and domestic frameworks for plastic waste collection with regulations in place for plastic waste export and movement.
ii. International market demand for plastic waste and liberalization of free trade in importing countries (e.g., China) and investment potential in recycled plastic raw material production in developing countries.
iii. International supply chain architecture in place involving transportation of containers, incurred customs charges and the huge costs of reverse haulage.
iv. Sources of plastic waste as they relate to the costs of non-renewable plastic materials and fossil fuel prices.
v. Development of technologically advanced and innovative products (new primary resins, bio-based composites, regenerative raw materials).

2. Vulnerability and volatility of biodegradable plastic markets

Manufacturing using plastic waste has become a huge business in several countries. The volume of the plastic market dramatically increased due to its use in industrial applications coupled with new packaging trends. Part of the popularity of using plastic waste materials is due to their recyclability and sustainability. In 2018, there were widespread bans on single-use plastic items, and most importantly, prohibitions against using synthetic plastic materials for packaging purposes. This led to the merger of two giant plastics manufacturers, Amcor and Bemis. Other industrial players demonstrated their

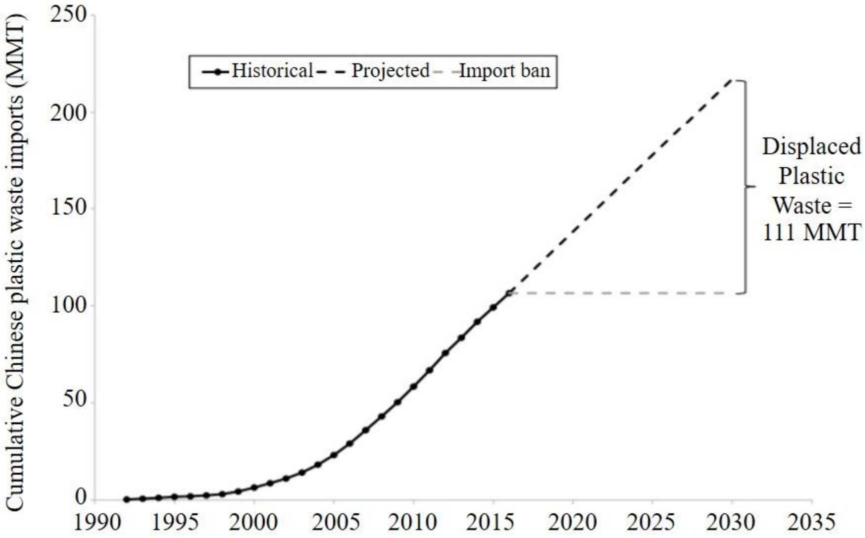

Figure 2 Projection of plastic waste importation prior to Chinese import ban [8]

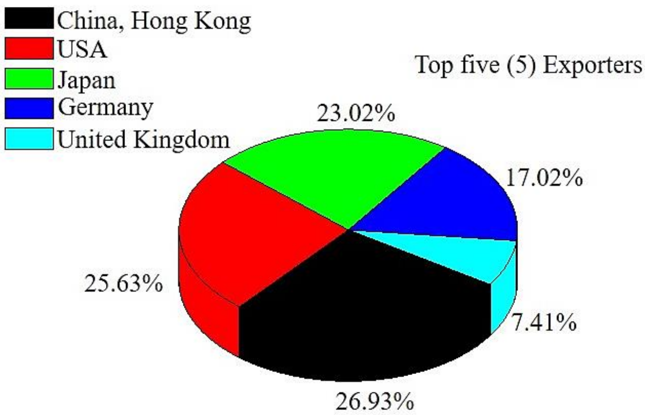

Figure 3 Top five exporting countries of waste plastic. Data were sourced from [9]

willingness to protect the future of plastic materials in the face of climate change. Plastics and bio-based materials are organic compounds. While plastic materials are partially synthetic, bio-based materials are 100% naturally derived [7]. The potential of the bio-based plastics market is huge owing to their great advantages. Several studies have shown that the world production of bio-based materials was 0.36 million Mt in 2007 with an approximate 40% annual increase. This projection of bio-based materials is based on the automobile industry's plan to substitute these materials for metal parts in vehicles. Part of the volatility in the bio-based market arises from various attempts to convert from petrochemical plastics to bio-based materials as reported by Nguyen et al. [10]. Despite all their shortcomings, the use of bio-based plastic materials is still rapidly growing with no projection of decline. The findings of several authors show the possibility of bio-based plastic production attaining a record 3.45 million Mt in 2020 [6]. Plastics from starch, polyhydroxyalkanoates (PHA) and bio based epoxy resin are potential future bio-based plastics. The Chinese ban on plastic wastes contributes to interest in bio-based material alternatives. This impact was felt worldwide due to the volatility of the plastic waste market. According to the US Financial Times, the price of plastic wastes in the UK during the economic downturn fell abruptly. Further reports indicated that most plastic film was sold at £22-£45 per Mt as of November 2008, a sharp decline from £130-£170 per Mt in January of the same year. In the same way, the price of waste 'natural' grade rHDPE bottles was also affected by the Chinese ban on plastic wastes. Market surveys showed that most of the high quality types of waste plastic traded at prices that sharply dropped from £260-330 in November 2008 to £130-150 in December of the same year, sparked by the global financial crisis. The European Union tried to reduce the volume of plastic wastes supplied to China to curtail further losses. This negatively impacted major developmental projects globally. Many packaging and construction works were halted for several years. The decline in global plastic wastes in 2008 was restored to full economic capacity in the summer of 2009. By June of 2009, the Chinese markets were able to cautiously import waste plastics. Full restoration of the high prices of used plastics was achieved in early 2010.

Recycling of plastic waste was later intensified after the global economic downturn, where China repositioned itself as a major player in the industry, as depicted in Figure 3. Hong Kong and China were fully dependent on each other based on an exchange of technological innovations. It can be deduced that further research is need to ascertain the sustainability of existing bio-based materials taking into consideration evolving wastes emanating from various applications.

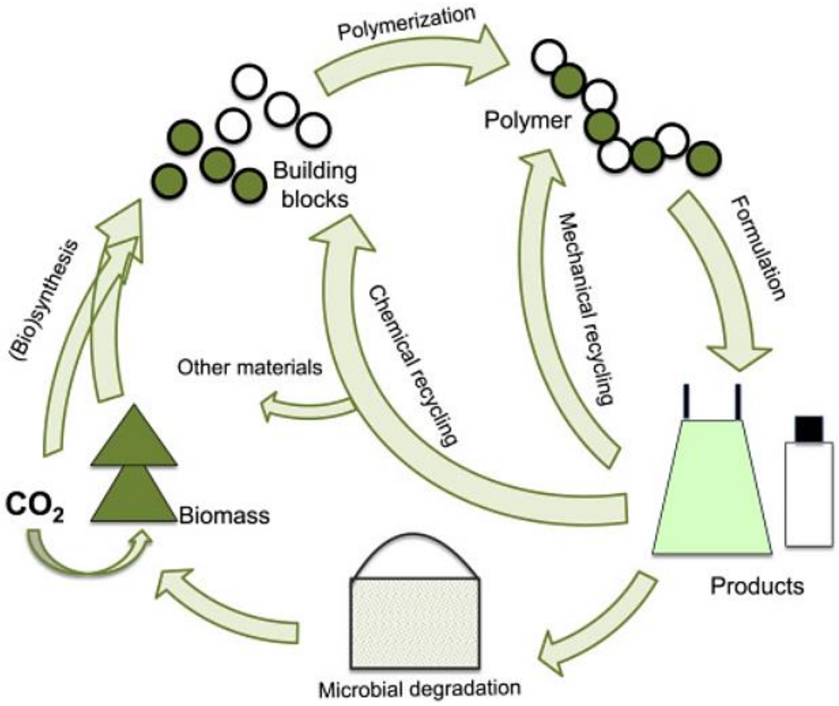

Figure 4 Emerging trend of bio-based plastics production and their future recycling approach

3. Trends of recycled biodegradable plastics

Plastics production is costly and accounts for an average of 6% of the global fossil energy used either as raw materials or during their manufacturing process. It is also estimated that global production of plastics was 335 million Mt in 2016 while the corresponding post-consumer plastic waste is approximately 150 million Mt per annum. There are fundamentally different approaches to plastic waste disposal in developing and emerging countries [11]. Depending on the technological innovations in some of these countries, three basic methods are generally employed. These are mechanical recycling, landfilling, and incineration. In developing countries, disposal and incineration are crudely used to minimize plastic waste volume [12]. Part of the concerns raised in numerous studies is the lack of sustainable plans in many developing countries where plastic wastes have created environmental disasters. The impact of climate change in some of these countries is severe and adaptive control must be adopted to effectively combat these problems. Particulate matter from environmental and plastic waste constitute hazards in many countries [13]. A considerable proportion of greenhouse gas emissions (GHG) are associated with their production. It is noteworthy that application of sophisticated incineration could pose dangers if their gas emissions are not properly channeled [14]. Part of the looming crisis is the more that 390 million Mt of CO_2 emissions recorded in 2012 [15] and the projection of 5% annual increases. The implication of this is that as plastic use increases, so does the amount fossil fuel required for its production. In total, this is about 20% of global energy consumption. The impact on GHG emissions is also expected to increase by about 15% with increases in the global annual carbon budget by 2050. The process of transition to an eco-friendly economy requires a holistic approach to the plastics value chain. This may involve an integrative approach, considering raw materials and energy used for production. Figure 4 reflects a process where production of plastics is entirely reclaimable from material design through their useful lifetime. In several emerging economies, attempts have been made to reduce the influence of fossil fuels on plastic production. This has led to the production of plastics based on renewable feedstocks as carbon-neutral alternatives to fossil-based products.

4. Looking beyond biodegradable plastic market

In order to proffer a sustainable solution to plastic waste management, it is therefore important to highlight alternative materials, ignoring of some of the shortcomings discussed in this paper [16]. Going by the volatility of biodegradable market and overdependence on China, it is very clear that better solutions still need to be sought to mitigate some of these challenges. Although the concept of bio-based materials has been explored with minimal progress, the these materials are best deployed in food packaging and those application whose end-of-life is less detrimental to the environment (e.g., agricultural films) [17]. This section is aimed at exploring other viable solutions to plastic waste management than reprocessing them into biodegradable plastic materials.

In several research studies [18-19], a good number of reports have projected polylactic acid (PLA) and polyhydroxyalkanoates (PHA) as viable materials for the future. In one study [20], progress was reported in the application of PLA to make computer accessories, component parts of batteries, and other home appliances, while PHA products are feasible in homes application and other disposable materials. Substantial obstacles in the adaptation of PLA and PHA may related to their high cost of production, limiting their market penetration and acceptability [21-23]. The findings of Wang et al. [24] detailed methods to lower PHA production costs and best manufacturing practices. Recent development have shown that some industrial companies have adopted a cradle-to-cradle approach in material development to sustain packaging innovation. For instance, Coca-Cola Company partially adopted used of 30% plant-regenerated PET bottles in 2011, and has just started using 100% plant-based PET bottles. This replacement to a larger extent will reduce the evolution of petrochemical PET while evolving bio-based PET, which can auto-degrade safely after its end-of-life phase [6, 25]. In another development, a renowned beer manufacturer, Carlsberg, recently showcased a sustainable wood-fibre based plastic can as part of their contribution to mitigate the impact of climate change and designing cradle-to-cradle packaging materials. These cases and many other new approaches are being explored to shift attention from the biodegradable plastic market.

In several studies [5, 26], there have been growing concerns expressed about some of the new innovations geared toward safe food production and environmental impact. In a typical scenario, findings showed that plastic bottles manufactured from bio-PET can reduce global warming 21% more than petroleum-sourced PET [27]. In the same paper, findings also showed that bio-PET performs worse in terms of eco-toxicity and ozone depletion. These contradictory results led to the development of a feedstock from microalgae [28]. Microalgae are group of diverse single-celled organisms that grow pools of fresh and salt-water. Reports have also shown that algae-derived chemicals can be used to produce bio-based polyesters [29-30]. A reasonable proportion of these species have been reported to contain high levels of oil and protein. In a another work, scientists [28] have shown that the microalgae, *Chlorella vulgaris*, and the cyanobacterium *Spirulina maxima*, contain reasonable proportions of protein, 51–58% and 60–71%, respectively, on a dry weight basis. In a similar paper, Zeller et al. [31] confirmed that an algae sourced polymer with 100% *Chlorella* is susceptible to brittleness. It was further confirmed that when plasticised, their structural properties were improved, thereby reducing the initial on-set of degradation. Another breakthrough is that some of these innovations include the development of yeast species and the use of food wastes to manufacture hydrocarbon waste feedstocks to yield plastics [32]. Recent work on diploid *Candida tropicalis* and its ability to transform fatty acids into viable omega-hydroxy fatty acids have been cited that could be further synthesized into PE-related polymers. Further research on food wastes, and most importantly, citrus oil, are also being undertaken and reported in the literature. Some researchers envision the prospects of producing more than 300 bio-plants from this process. In similar work, Byrne et al. [33] identified a process of producing limonene oxide with CO_2 to make polymeric polylimonene carbonate. In a related development, researchers across Europe are also formulating new methods of developing a prototype bio-refinery. This approach is believed to transform orange peel waste into gasses which can further be processed into liquid materials with the aid of high-power microwaves. Theoretically, limonene can also be transformed into an epoxide and reprocessed with carbon (IV) oxide with the aid of a zinc based catalyst to form a polymer based structure [33]. The resulting limonene-polycarbonate is being researched to produce several other polymers.

Another published paper [34] projected the prospects of producing new plastic materials from nanoscale materials. Nanotechnologies are basically the control of matter at very small dimensions, normally between 1 and 100 nm. Research findings show that the products made using this technology are classified into two types, nano-materials (NMs) and free nano-particles (NPs). Further investigation showed that the physical and chemical properties of these nanomaterials are different from their bulk materials. This further broadens the potential to expand research on these important properties, especially on weight reduction through the adoption of nanocomposites and nanosilica. Mechanical strength can be enhanced through the introduction of carbon nanotubes into these materials. It may be possible to incorporate antimicrobial activities into new plastic materials through inclusion of nano-Ag. With these developments, the plastic industry is expected to use nanoscale materials to improve material properties [35].

5. Conclusions

The aim of this research is to explore the volatility of the biodegradable plastics market and suggest approaches to sustainable plastic materials that do not cause environmental crises. China is the major importer of waste plastics. They were financially challenged in 2008 leading to a reduction in their activity in plastic waste management. In this research, it is evident that the long-term stability of plastic materials is crucial in many industrial applications, especially their end-of-life phase. The market for bio-based or biodegradable plastics has increased with huge investment in production of these plastic materials. It has also been reported that the biodegradability of these materials largely depends on their chemical structure and the constituent compounds used in their production, but not necessarily the carbon proportion of the polymers. It has also been established that the degradation of bio-based end-products under varying conditions are sometimes unknown. The future predictions of this paper focus on the concept of “beyond biodegradable”, which projects new polymer bio-based materials and additives that will be adapted for industrial application using technological innovations. The new challenge will then be for the industrial players to correctly choose from these new materials. It should be noted that bio-based plastic materials are still suitable for application if their recycled waste feedstock are tolerated by the environment. From a waste management perspective, biodegradable plastic materials should degrade naturally with negligible emissions into the environment.

6. Acknowledgements

The authors appreciate the National Research Foundation (NRF) and Department of Science and Technology (DST), South Africa, for funding the fellowship leading to the manuscript. Gratitude also goes to the School of Chemical and Metallurgical Engineering, Faculty of Engineering and Built Environment, University of the Witwatersrand, for providing the platform to conduct this research. The authors equally appreciate the useful comments received from the two anonymous reviewers and the guest editor who handled our paper.

7. References

[1] Campuzano F, Brown RC, Martínez JD. Auger reactors for pyrolysis of biomass and wastes. Renew Sustain Energ Rev. 2019;102:372-409.

[2] Abila N. Managing municipal wastes for energy generation in Nigeria. Renew Sustain Energ Rev. 2014;37:182-90.

[3] Adekomaya O, Jamiru T, Sadiku R, Huan Z. Minimizing energy consumption in refrigerated vehicles through alternative external wall. Renew Sustain Energ Rev. 2017;67:89-93.

[4] Babayemi JO, Nnorom IC, Osibanjo O, Weber R. Ensuring sustainability in plastics use in Africa:

consumption, waste generation, and projections. Environ Sci Eur. 2019;31:1-20.
[5] Permana AS, Towolioe S, Aziz NA, Ho CS. Sustainable solid waste management practices and perceived cleanliness in a low income city. Habitat Int. 2015;49:197-205.
[6] Oyake-Ombis L, van Vliet BJM, Mol APJ. Managing plastic waste in East Africa: Niche innovations in plastic production and solid waste. Habitat Int. 2015;48:188-97.
[7] Ezeah C, Roberts CL. Analysis of barriers and success factors affecting the adoption of sustainable management of municipal solid waste in Nigeria. J Environ Manag. 2012;103:9-14.
[8] Brooks AL, Wang S, Jambeck JR. The Chinese import ban and its impact on global plastic waste trade. Sci Adv. 2018;4(6):1-7.
[9] Velis C. Global recycling markets: plastic waste a story for one player - China. Vienna: ISWA; 2014.
[10] Nguyen TTP, Zhu D, Le NP. Factors influencing waste separation intention of residential households in a developing country: Evidence from Hanoi, Vietnam. Habitat Int. 2015;48:169-76.
[11] Choklob W, Gupta RK, Kajorncheappunngam S. PLA blend/RHA permeable composite films for fruit packaging. Eng Appl Sci Res. 2019;46(3):210-8.
[12] Srimanta P, Hovichit P. Evaluation of greenhouse gas reduction from improvement of solid waste management of Khon Kaen University. KKU Eng J. 2013;40(2):203-12.
[13] Abulude F, Fagbayide S, Akinnusotu A, Elisha J, Makinde O. Particulate matter and source identification: A case study of Nigeria. Eng Appl Sci Res. 2019;46(2):151-69.
[14] Laonapakul T. Synthesis of hydroxyapatite from biogenic wastes. KKU Eng J. 2015;42(3):269-275.
[15] Hatti-Kaul R, Nilsson LJ, Zhang B, Rehnberg N, Lundmark S. Designing biobased recyclable polymers for plastics. Trends Biotechnol. 2020;38(1):50-67.
[16] Lambert S, Wagner M. Environmental performance of bio-based and biodegradable plastics: the road ahead. Chem Soc Rev. 2017;46(22):6855-71.
[17] Mohanty AK, Misra M, Drzal L. Sustainable bio-composites from renewable resources: opportunities and challenges in the green materials world. J Polymer Environ. 2002;10:19-26.
[18] Wang Y, Pham DT, Ji C. Self-healing composites: a review. Cogent Eng. 2015;2(1):1075686.
[19] Maaß S, Daphi D, Lehmann A, Rillig MC. Transport of microplastics by two collembolan species. Environ Pollut. 2017;225:456-9.
[20] Vink ET, Rábago KR, Glassner DA, Springs B, O'Connor RP, Kolstad J, et al. The sustainability of NatureWorks™ polylactide polymers and Ingeo™ polylactide fibers: an update of the future. Macromol Biosci. 2004;4:551-64.
[21] Philip S, Keshavarz T, Roy I. Polyhydroxyalkanoates: biodegradable polymers with a range of applications. J Chem Tech Biotechnol. 2007;82(3):233-47.
[22] Chen GQ. A microbial polyhydroxyalkanoates (PHA) based bio-and materials industry. Chem Soc Rev. 2009;38(8):2434-46.
[23] Lettner M, Schöggl JP, Stern T. Factors influencing the market diffusion of bio-based plastics: results of four comparative scenario analyses. J Clean Prod. 2017;157:289-98.
[24] Wang Y, Yin J, Chen GQ. Polyhydroxyalkanoates, challenges and opportunities. Curr Opin Biotechnol. 2014;30:59-65.
[25] Fu H, Li Z, Wang R. Estimating municipal solid waste generation by different activities and various resident groups in five provinces of China. Waste Manag. 2015;41:3-11.
[26] Adekomaya O, Jamiru T, Sadiku R, Huan Z. Sustaining the shelf life of fresh food in cold chain – a burden on the environment. Alexandria Eng J. 2016;55(2):1359-65.
[27] Chen L, Pelton RE, Smith TM. Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles. J Clean Prod. 2016;137:667-76.
[28] Trivedi J, Aila M, Bangwal D, Kaul S, Garg M. Algae based biorefinery—how to make sense?. Renew Sustain Energ Rev. 2015;47:295-307.
[29] Noreen A, Zia KM, Zuber M, Ali M, Mujahid M. A critical review of algal biomass: A versatile platform of bio-based polyesters from renewable resources. Int J Biol Macromol. 2016;86:937-49.
[30] Zia KM, Noreen A, Zuber M, Tabasum S, Mujahid M. Recent developments and future prospects on bio-based polyesters derived from renewable resources: a review. Int J Biol Macromol. 2016;82:1028-40.
[31] Zeller MA, Hunt R, Jones A, Sharma S. Bioplastics and their thermoplastic blends from Spirulina and Chlorella microalgae. J Appl Polymer Sci. 2013;130(5):3263-75.
[32] Lu W, Ness JE, Xie W, Zhang X, Minshull J, Gross RA. Biosynthesis of monomers for plastics from renewable oils. J Am Chem Soc. 2010;132(43):15451-5.
[33] Byrne CM, Allen SD, Lobkovsky EB, Coates GW. Alternating copolymerization of limonene oxide and carbon dioxide. J Am Chem Soc. 2004;126(37): 11404-5.
[34] Bystrzejewska-Piotrowska G, Golimowski J, Urban PL. Nanoparticles: their potential toxicity, waste and environmental management. Waste Manag. 2009;29(9):2587-95.
[35] Roes L, Patel MK, Worrell E, Ludwig C. Preliminary evaluation of risks related to waste incineration of polymer nanocomposites. Sci Total Environ. 2012;417-418:76-86.